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Characterization of Picometer Repeatability Displacement Metrology Gauges

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Abstract – A facility to test the linearity and drift of heterodyne laser metrology gauges for measuring distances of 1 to 7 meters with 10 picometer repeatability is described.

1 INTRODUCTION

The Space Interferometry Mission (SIM) [1,2] scheduled for launch in 2009, is an optical stellar interferometer with a 10 meter baseline capable of micro-arcsecond accuracy astrometry. SIM will measure relative angular positions of ~3000 stars to a 5 picoradian accuracy. Such observations, repeated over the 3 year mission duration, are expected to find earth-sized planets orbiting stars (detecting the star's motion about the system's center-of-mass), yield new data on the distribution of mass (both visible and "dark matter") in this galaxy and the nearest neighbouring galaxies, and provide mass determinations of the dark, compact objects causing gravitational microlensing events. (A complete list of

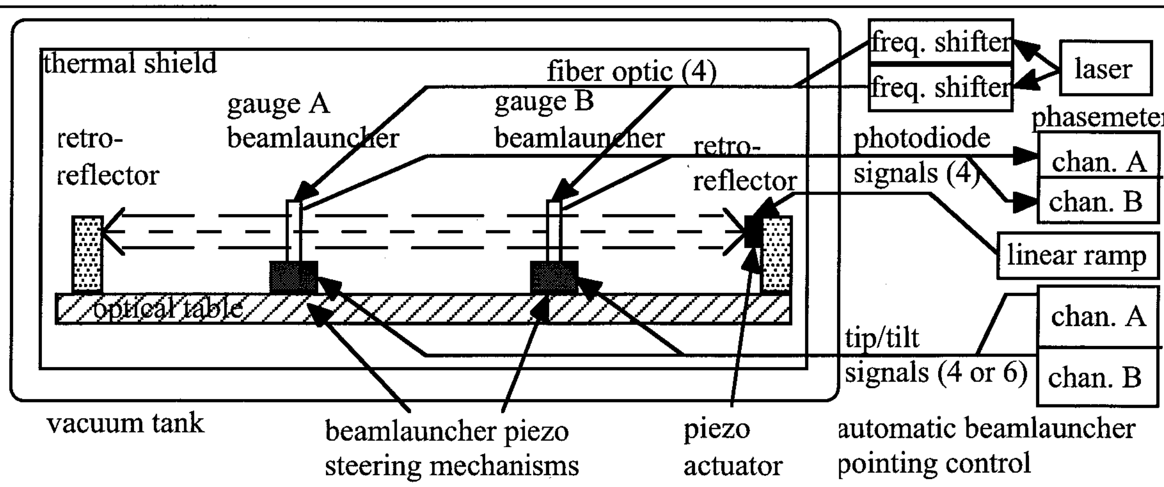

Figure 1. Metrology test facility. 1.3 micron laser output is split and shifted to create a 100 kHz frequency difference, which is seen as a 100 kHz heterodyne signal at the photodiodes. Gauge A's measurement beam (long dash) and gauge B's (short dash) both measure the distance between the retroreflectors. Fold mirrors (not shown) are used to achieve a longer inter-fiducial distance.

scientific objectives is available at http://sim.jpl.nasa.gov.)

While the angular measurements are carried out with white light interferometers, changes in the underlying geometry of SIM's optical system must be monitored to an accuracy $e=aD$=(5 picoradians)(10 meters)=50 picometers rms, where a is the desired angular accuracy, D is the interferometer baseline, and e is the resulting metrology requirement. This is to be maintained over the timescale of roughly 1000 seconds. Accounting for geometric factors and error contributions from sources other than metrology, the error budgeted to each metrology interferometer is e=10 picometers rms.

The metrology system [3] comprises (1) a 1.3 micron laser source, (2) frequency shifters that split the light into two frequencies, separated by 100 kHz, (3) optical fibers to bring the light to (4) "beamlaunchers", Michelson interferometers that probe the distance between (5) corner-cube retroreflector fiducials placed at the vertices of a triangular lattice that are the basis SIM's geometry, (6) photodiodes to detect the heterodyne outputs of the beamlauncher, and (7) phase detecting electronics to convert the photodiode signal into a distance between the fiducials.

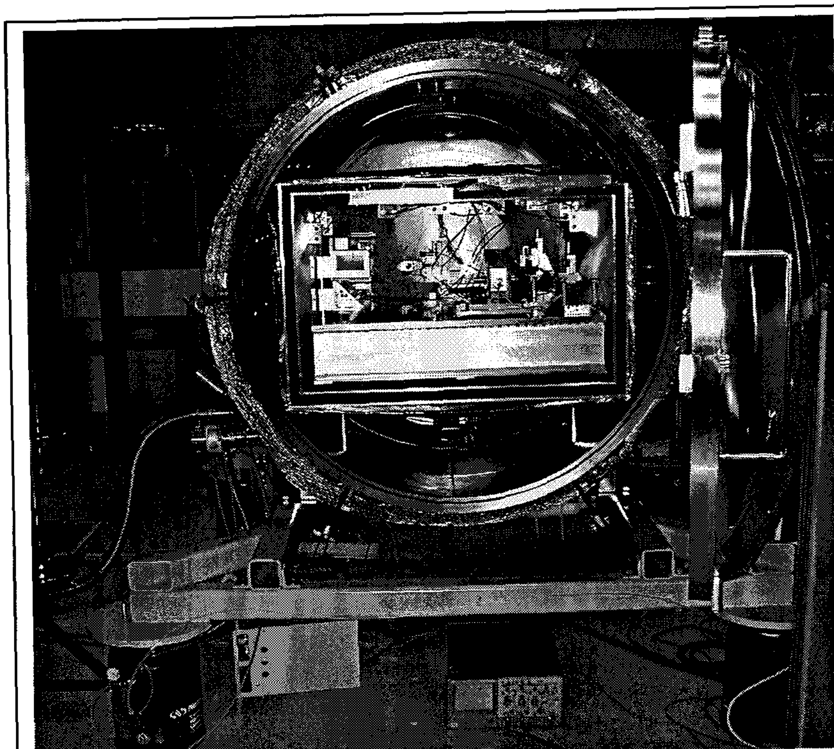

Figure 2. Test facility, showing 122 cm diameter, 130 cm length, vacuum tank mounted on pneumatic vibration isolators. Outer insulation, inner thermal shields with multilayer insulation, decouple the optical table from ambient temperature variations.

It is the internal *angles* of the triangles, which have sides of several meters in length and are defined by the retroreflector fiducials, that are crucial. Since angles are unaffected by scale errors, common mode effects such as slow laser wavelength drift are not a concern, and will not be discussed here. Rather, the focus of this work is on improving the beam-launchers' linearity and thermal stability.

The metrology system

will operate in an environment where the temperature will be stable to 1 milliKelvin within the measurement timescale, setting a temperature coefficient requirement $C=e/\Delta T=10$ nm/K.

The design of metrology gauges meeting these requirements requires various resources, including the means to test prototypes' performance. The remainder of this paper describes the facility constructed at JPL to test metrology gauges

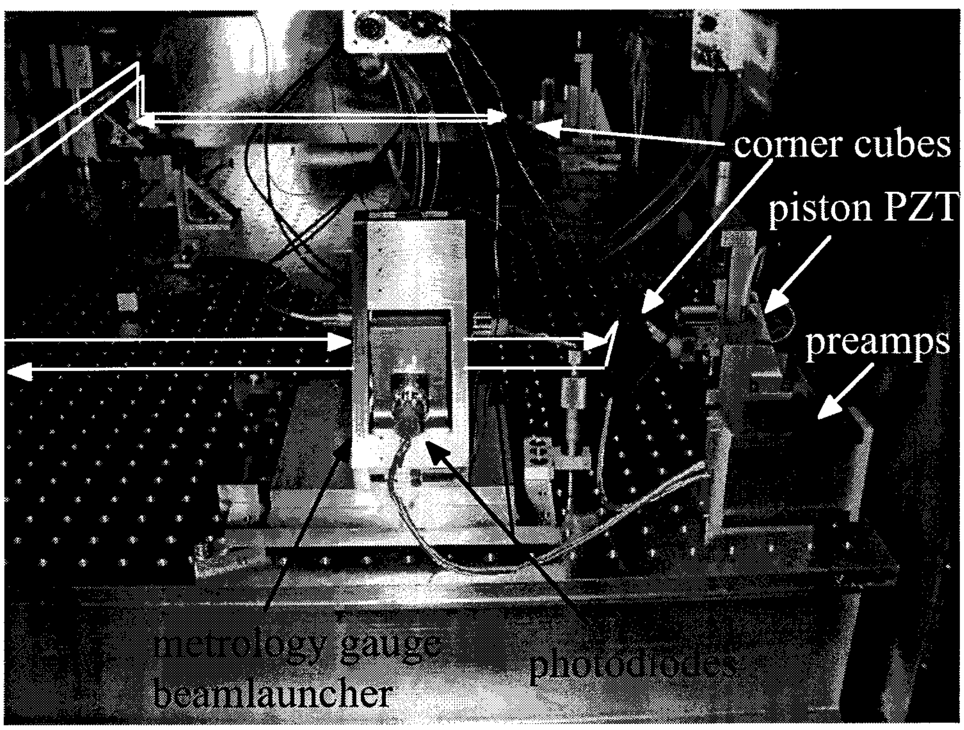

Figure 3. Metrology gauge under test for linearity. The corner cube retro-reflector at the right is on a Burleigh PZS-100-V piezo stage, which gives about 100 microns of motion in the direction of the beam. White arrows show path of measurement beam which travels to the right and traces a path between the corner cubes and re-enters the launcher from the left. Fold mirrors allow a 2.3 meter inter-fiducial distance within a limited area.

and provide designers feedback.

2 THE "TWO-GAUGE" TEST FACILITY

The metrology test facility (figures 1,2) can simultaneously test two prototype beamlaunchers.

The beamlaunchers under test are positioned between the corner cubes and aligned such that the measurement beams are parallel to a line connecting the corner cube fiducials. (The beamlaunchers are designed to allow each other's beam to pass through unimpeded.) The tank is evacuated (for the thermal

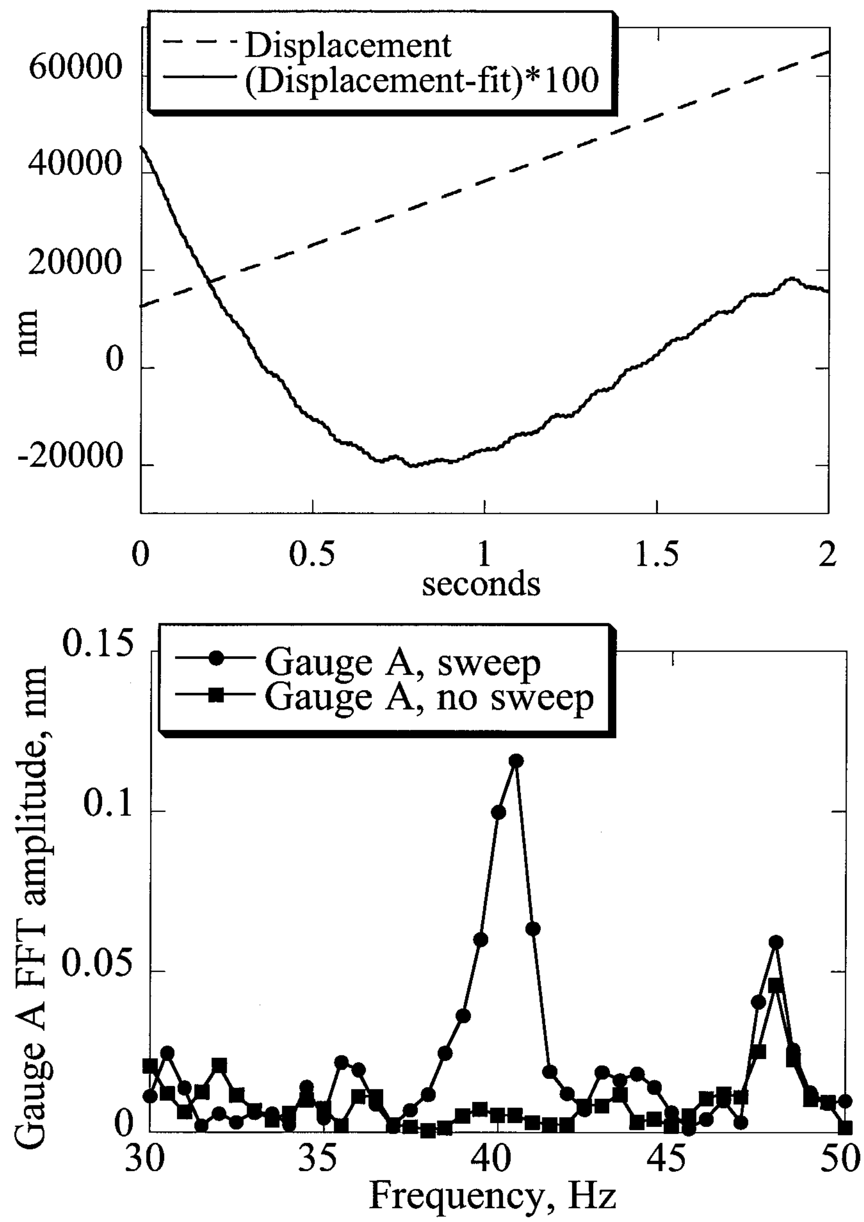

Figure 4. Typical nonlinearity test data. The upper plot shows the ~50 micron near-linear motion of the retroreflector (dashed) and the same data, detrended and magnified by 100 (solid) to show deviations from linear motion caused by (a) piezo non-linearity (parabola-like effect), (b) mechanical resonances (8 Hz sinusoid) and (c) beamlauncher cyclic nonlinearity, which is too small to be seen directly. The *lower* plot shows the magnitude of the Fourier transform of the same data (solid circles) around the frequency $f = 2v/\lambda$=40 Hz where a ~130 pm cyclic nonlinearity is evident. (The 80 and 120 Hz components were undetectable.) For comparison, data with no linear motion are also shown (solid squares).

tests), and the measured inter-fiducial distance is monitored by the phase meter hardware and recorded by the computer system. In principle, the two gauges should agree exactly. Comparing the two gauges provides a sensitive test of the gauges' performance.

3 LINEARITY

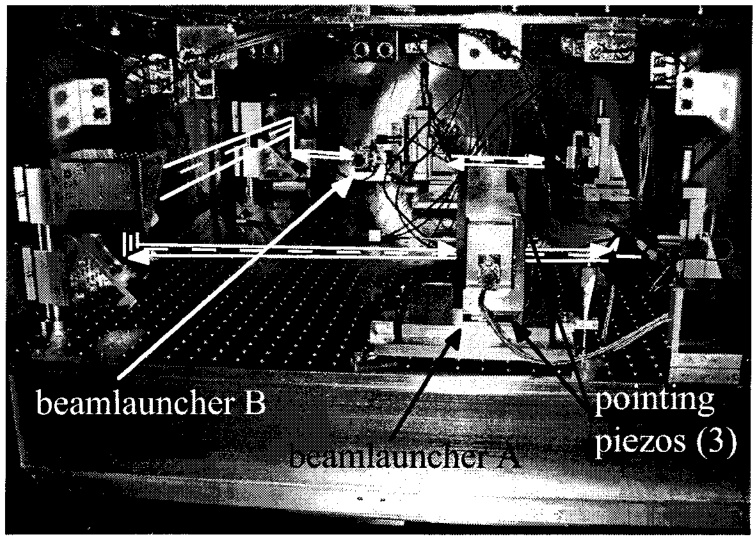

Figure 5. View of beamlaunchers and optical paths of measurement beams A (solid) and B (dashed). Also visible are 2 of the 3 piezo actuators for elevation & azimuth steering of launcher A, used to prevent mispointing errors.

The "external" portion of SIM metrology should be linear to 10 pm, over motions of less than 1 mm (but over separations of 1 to 7 meters). The dominant nonlinearity over this scale is premature mixing of the reference and measurement laser beams. To first order, the resulting error has the form $e = m\sin(\pi L/\lambda)$, where L is the separation between fiducials, and λ is the laser wavelength. Higher order errors, $e = m_n \sin(n\pi L/\lambda)$, n=2,3,4… are also possible.

The measurement of cyclic error requires only one gauge, which is placed in the apparatus as shown in figure 3. The corner cube moves at constant velocity v, and the distance measured by the gauge under test is recorded. Typical data are shown in figure 4. After removing the linear component, the magnitude of the Fourier transform of the data is calculated. The cyclic error e is observable as peaks at frequencies $f = 2nv/\lambda$. Usually only the fundamental n=1 frequency contributes significantly.

4 TEMPERATURE COEFFICIENT

Thermal sensitivity will be measured by placing two beamlauncher between the same pair of corner-cube fiducials, creating two gauges that measure the same distance. The beamlaunchers are designed such that beam of launcher "A" passes through launcher "B", and vice-versa.

Repetitive temperature excursions of magnitude 10 mK to 100 mK will be applied to one launcher. The repetition rate will be about 1 cycle/hour. The experiments will be carried out in vacuum to mimic operating conditions in SIM and to eliminate the temperature coefficient of air. The launchers' temperatures are controlled by heaters (up to 10 mW will be needed), and monitored by platinum resistance temperature detectors (RTDs) which are read by a resistance bridge, to 1 mK precision.

The temperature stability on the optical table is better than 1 mK per hour, owing to the thermal mass of the tank and thermal shields, and the insulating properties of the vacuum and insulating blankets. Additional blankets will be installed to thermally decouple the two beamlaunchers being compared.

By taking the difference of the two gauges' data, we remove most thermally induced errors, such as expansion of the optical table. However a source of error that is not common-mode is mispointing of the beam launchers. If the metrology beam is not parallel to a line connecting the corner cube vertices, a temperature dependence dL/dT will be seen. $dL/dT = -L_O \theta_O d\theta / dT$ = -(2 meters)(100 μrad)(22x10^{-6} K^{-1}) = 4.4 nm per mK, where L_O is the distance between fiducials, 100 microradians is a typical alignment error after manual adjustments and 22 ppm/K is the expansion coefficient of the supporting aluminum, which is numerically equal to the worst case bending effect of a temperature gradient applied to the beamlauncher mounting hardware. To prevent this error an automatic pointing control system has been implemented [4].

5 RECENT RESULTS

The JPL metrology effort has thus far demonstrated cyclic non-linearities of less than 100 pm rms. The testing of temperature coefficients is currently underway and will be presented at the conference.

6. ACKNOWLEDGEMENT

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